Self-Latching Shape Memory Piezocomposite Control Surface

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Overview

- Background:
  - Piezocomposite technology and aeronautics applications (SOA)
  - *Self-latching piezocomposite concept* (this effort)
- Phase I activities:
  - Self-latching actuator proof-of-concept demonstration
  - Mathematical model validation efforts
  - Optimization for self-latching
- Future work; Phase II plans:
  - Self-latching control surface fabrication
  - Wind tunnel validation

Piezocomposite Actuators

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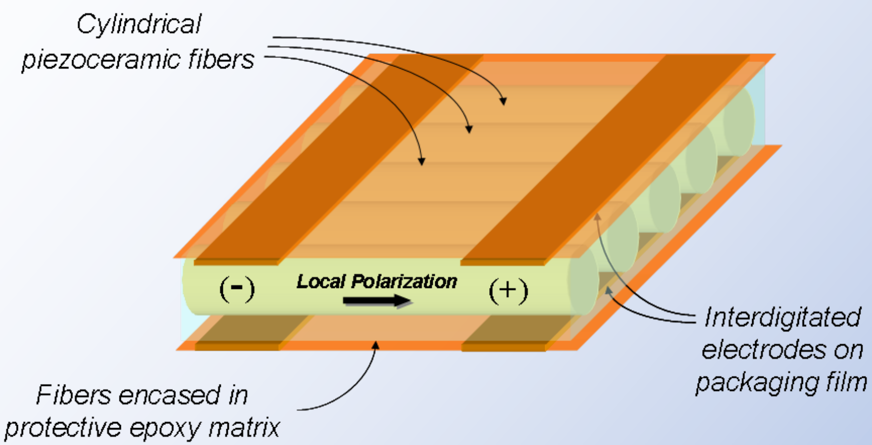
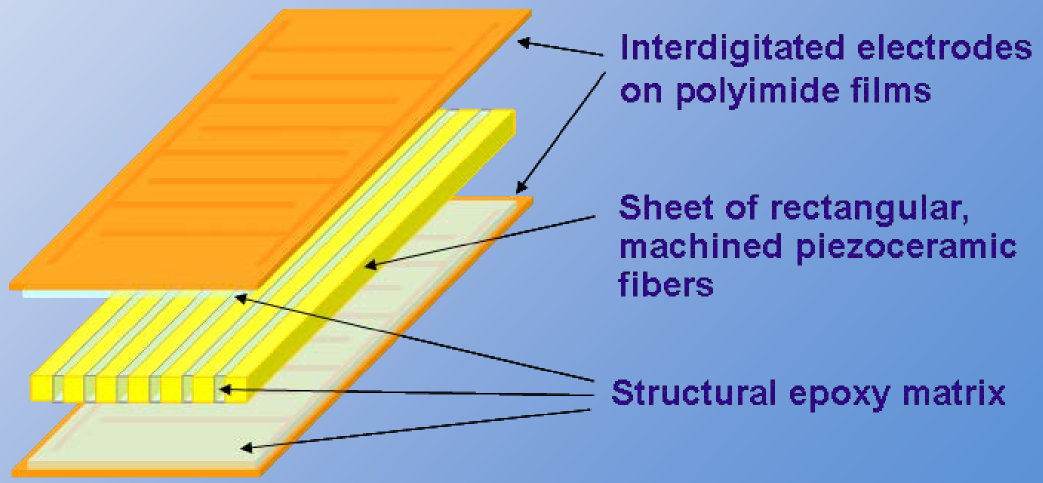


AFC

(Bent, Hagood, et al, 1993-2000)

MFC

(NASA, 1997-2003)



Active Blade Twist Control for Vibration Reduction

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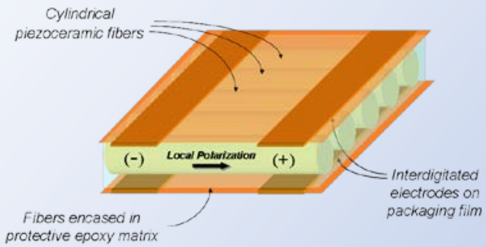
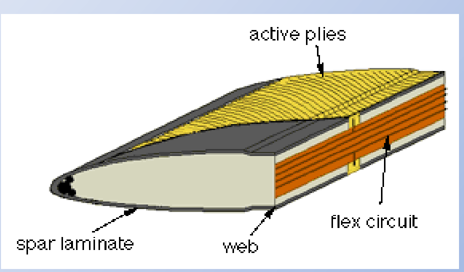
1. Piezoelectric Composite Actuator

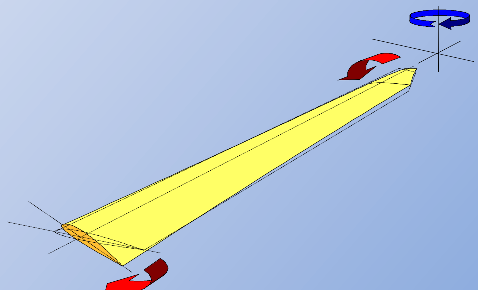


2. Active Fiber Composite Plies

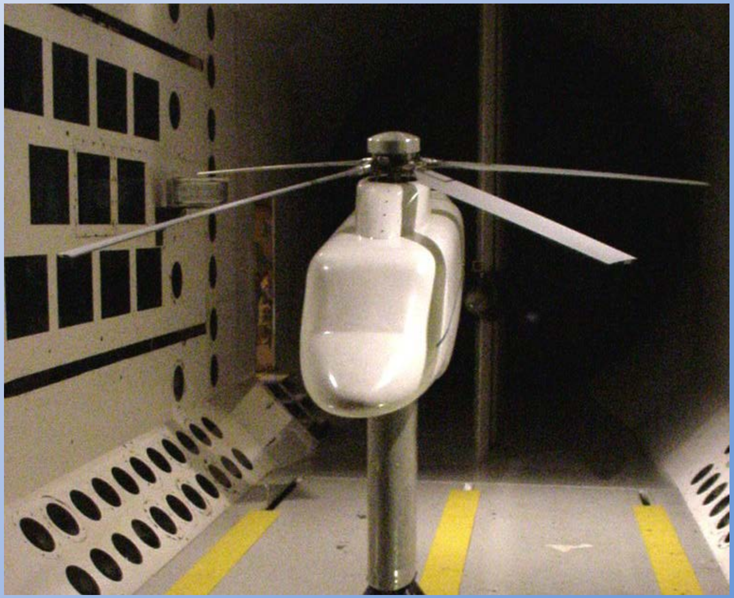
3. Active Composite Structure

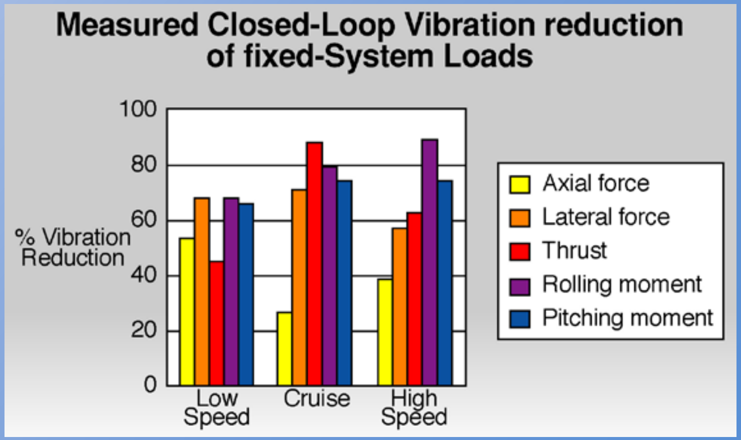


4. Active Twist Control



Active Twist Rotor In Wind Tunnel





Solid-State Piezocomposite Control for Small Aircraft

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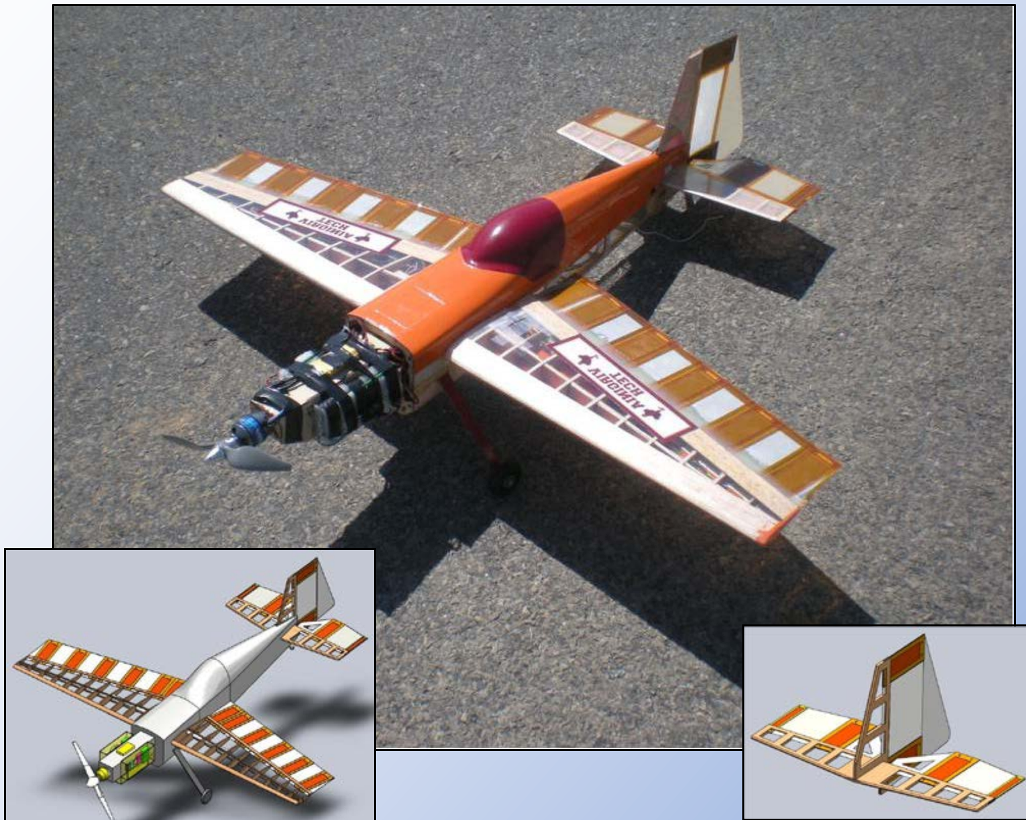

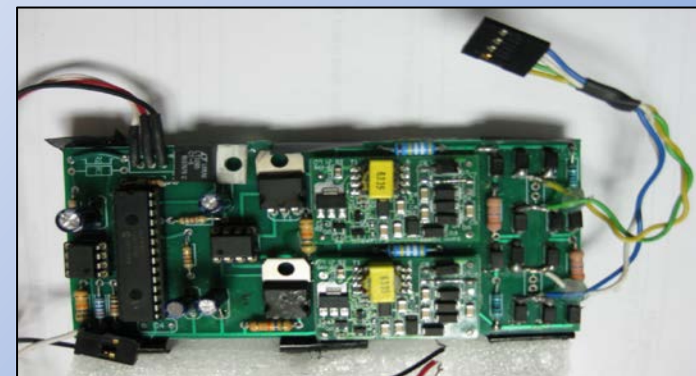

http://www.youtube.com/user/VTWMD

Ref: Bilgen, 2013

Can we create a piezocomposite control surface that does not require power to maintain a deflection?

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Shape Memory Ceramics

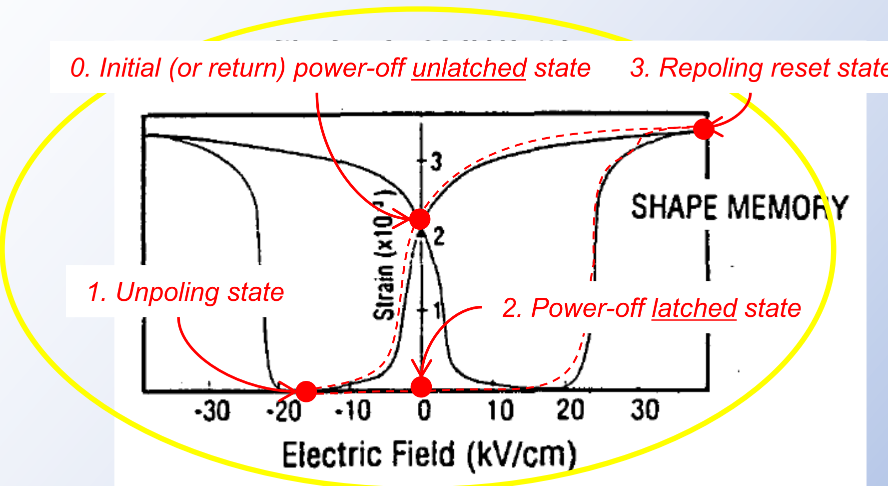

Fig.2 Field-induced strain curves for the lead z stannate system $Pb_{0.99}Nb_{0.02}((Zr_xSn_{1-x})_{1-y}Ti_y)$ Top: x = 0.060, and bottom: x = 0.065.

Ref: Uchino, K., "Recent Trend of Piezoelectric Actuator Developments," IEEE International Symposium on Micromechatronics and Human Science, 1999.

2.3 Phase-Change Materials

Concerning the phase-change-related strains, polarization induction by switching from an antiferroelectric to a ferroelectric state, has been proposed [10]. Figure 2 shows the field-induced strain curves taken for the lead zirconate stannate based $Pb_{0.99}Nb_{0.02}((Zr_xSn_{1-x})_{1-y}Ti_y)_{0.98}O_3$ system. The longitudinally induced strain reaches up to 0.4%, which is larger than that expected in normal piezostrictors or electrostrictors. A rectangular-shape hysteresis in Fig.2 top, referred to as a "digital displacement transducer" because of the two on/off strain states, is interesting. Moreover, this field-induced transition exhibits a shape memory effect in appropriate compositions (Fig.2 bottom). Once the ferroelectric phase has been induced, the material will "memorize" its ferroelectric state even under zero-field conditions, although it can be erased with the application of a small reverse bias field [11]. This shape memory ceramic is used in energy saving actuators. A latching relay is composed of a shape memory ceramic unimorph and a mechanical snap action switch, which is driven by a pulse voltage of 4ms. Compared with the conventional electromagnetic relays, the new relay is much simple and compact in structure with almost the same response time.

[10] K.Uchino and S.Nomura, Ferroelectrics, **50**(1), 191 (1983)
[11] A.Furuta, K.Y.Oh and K.Uchino, Sensors and Mater., 3(4), 205 (1992)

Is there a self-latching effect in MFC piezocomposites?

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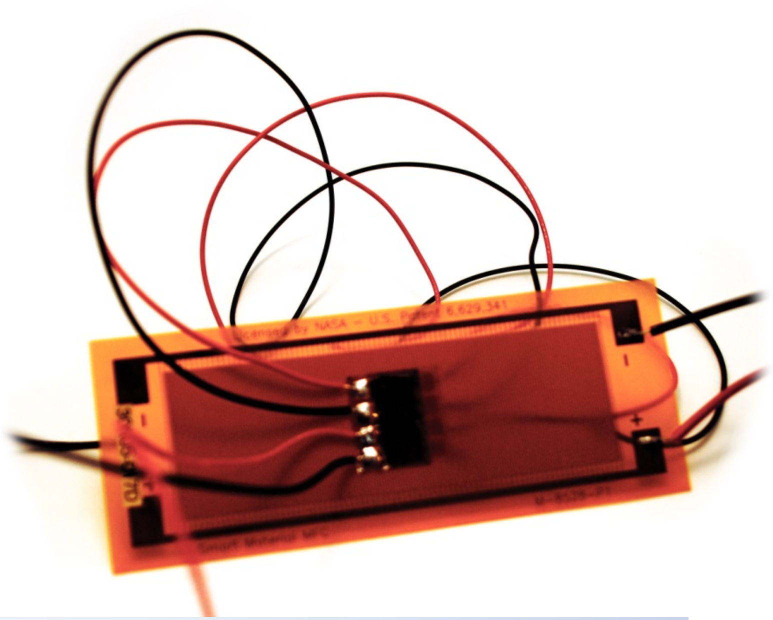
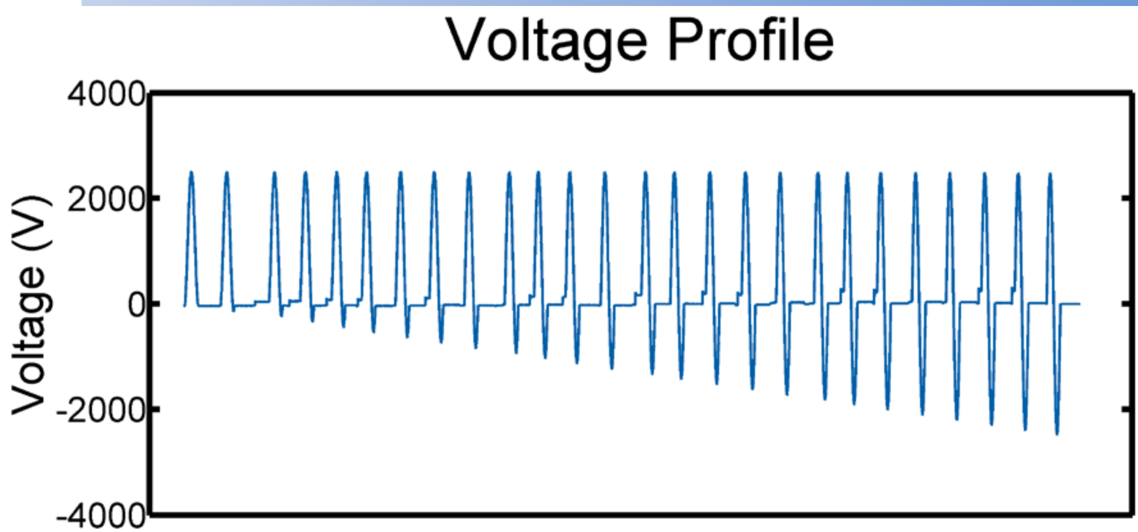


Initial Test

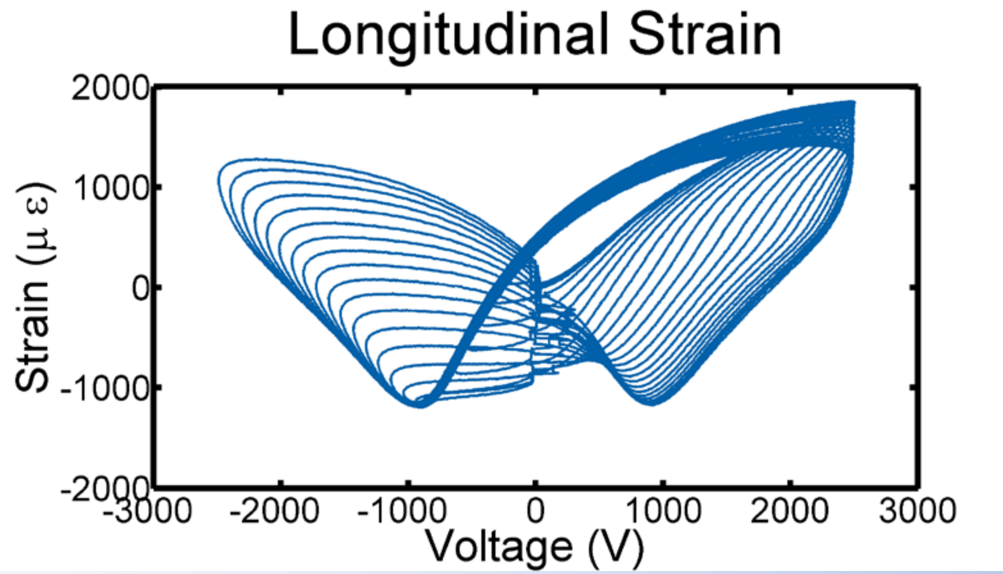
- *Several tests ran in which the MFC is fully poled and then a negative back field is applied.*
- *Negative back field ranged from 0 to -2500V in increments of -100V.*

Goal

- *Remnant strain can be controlled with partial poling/depoling.*
- *By varying the back field magnitude, the effect on the remnant polarization is found.*

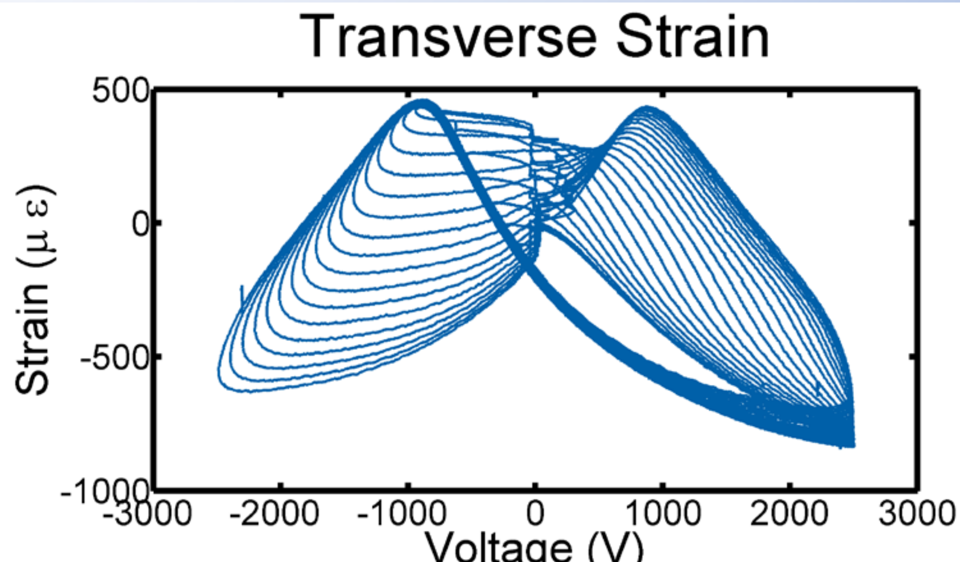


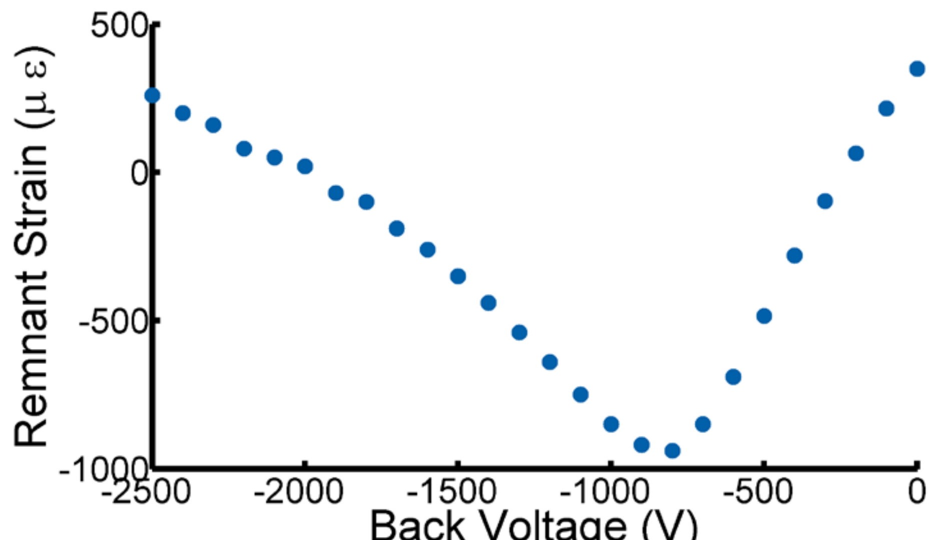
Latching effect proof-of-concept with PZT-5H-based MFC demonstrated



Results

- *Varied back field initially causes partial depoling which reduces remnant strain.*
- *Eventually increasing back field causes the material to repole and the remnant strain increases.*





Can we model and predict or design for this effect?

Linear Piezoelectric Finite Element Formulation

Initial Weak Form:

$$\int_{\Omega} \left\{ \sigma_{ij}\delta\varepsilon_{ij} - D_i \delta E_i \right\} d\Omega = \int_{\Omega} \left\{ b_i \delta u_i \right\} d\Omega + \int_{\Gamma} \left\{ t_i \delta u_i - \omega \delta\phi \right\} d\Gamma$$

Constitutive Laws:

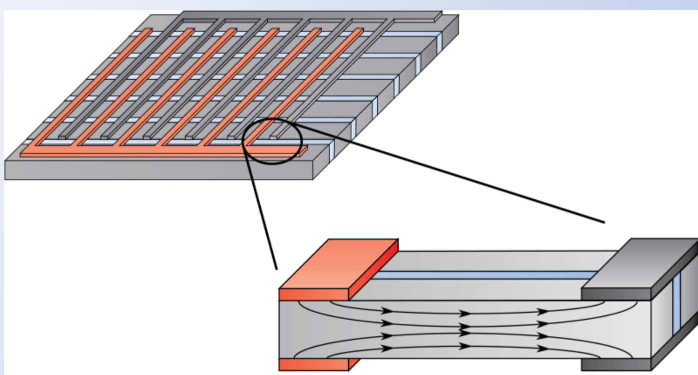
$$\sigma_{ij} = c^{E}_{ijkl}\left(\varepsilon_{kl} - \varepsilon^{r}_{kl}\right) - e_{kij}E_k$$

$$D_i - P^{r}_{i} = e_{ikl}\left(\varepsilon_{kl} - \varepsilon^{r}_{kl}\right) + \kappa^{\varepsilon}_{ij}E_j$$

FEM Discretized Governing Equations:

$$\left(K_{uu}\right)^{ab}_{ik}\tilde{u}^{b}_{k} + \left(K_{u\phi}\right)^{ab}_{i}\tilde{\phi}^{b} = \int_{\Omega}\left\{ c^{E}_{ijkl}\varepsilon^{r}_{kl}N^{u}_{a,j} \right\} d\Omega + \int_{\Omega}\left\{ b_i N^{u}_{a} \right\} d\Omega + \int_{\Gamma}\left\{ t_i N^{u}_{a} \right\} d\Gamma$$

$$\left(K_{\phi u}\right)^{ab}_{k}\tilde{u}^{b}_{k} - \left(K_{\phi\phi}\right)^{ab}\tilde{\phi}^{b} = \int_{\Omega}\left\{ \left(e_{ikl}\varepsilon^{r}_{kl} - P^{r}_{i}\right) N^{\phi}_{a,i} \right\} d\Omega - \int_{\Gamma}\left\{ \omega N^{\phi}_{a} \right\} d\Gamma$$



Stiffness Matrix Name	Stiffness Definition
Stiffness Matrix	$\left(K_{uu}\right)^{ab}_{ik} = \int_{\Omega}\left\{ N^{u}_{a,j} c^{E}_{ijkl} N^{u}_{b,l} \right\} d\Omega$
Piezoelectric 'Stiffness'	$\left(K_{u\phi}\right)^{ab}_{i} = \int_{\Omega}\left\{ e_{kij} N^{\phi}_{b,k} N^{u}_{a,j} \right\} d\Omega$
Piezoelectric 'Stiffness'	$\left(K_{\phi u}\right)^{ab}_{k} = \int_{\Omega}\left\{ e_{ikl} N^{u}_{b,l} N^{\phi}_{a,i} \right\} d\Omega$
Dielectric 'Stiffness'	$\left(K_{\phi\phi}\right)^{ab} = -\int_{\Omega}\left\{ \kappa^{\varepsilon}_{ij} N^{\phi}_{a,i} N^{\phi}_{b,j} \right\} d\Omega$

FEM Model

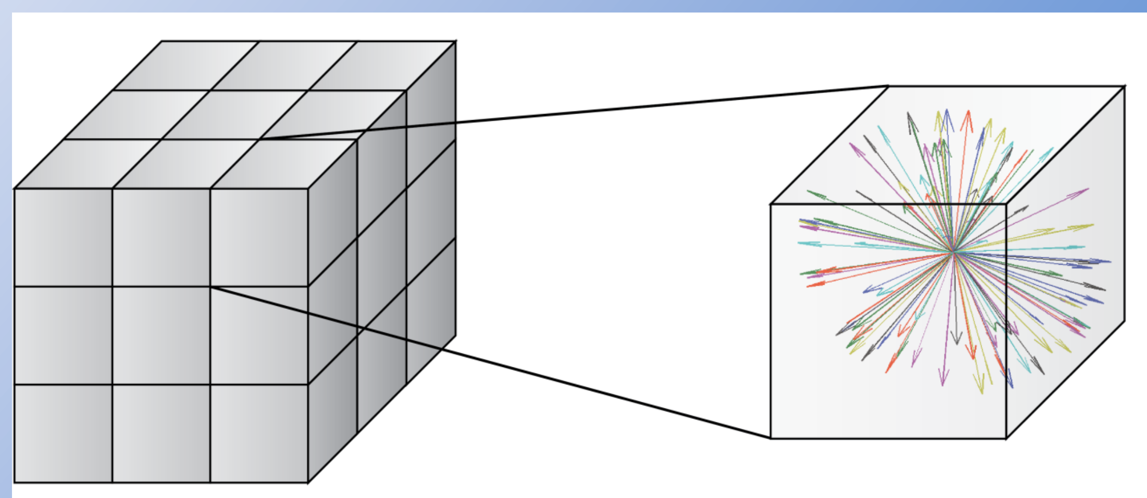
Micromechanical Switching Routine

General Description

- *Stress, electric field and remnant values dictated by linear FEM.*
- *No grain to grain interactions*
- *Switching criterion reorients the grain changing the remnant polarization and remnant strain. This is fed back into the linear FEM code.*

Switching Criterion

$$E_i \Delta P_i^r + \sigma_{kl} \Delta \varepsilon_{kl}^r \geq W_{ab}$$



FEM Model

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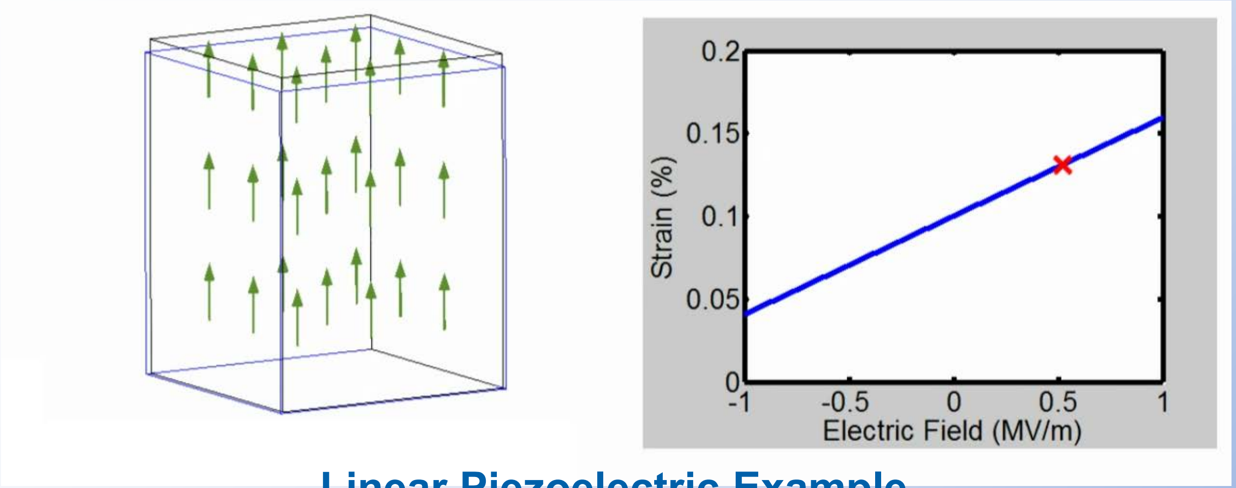
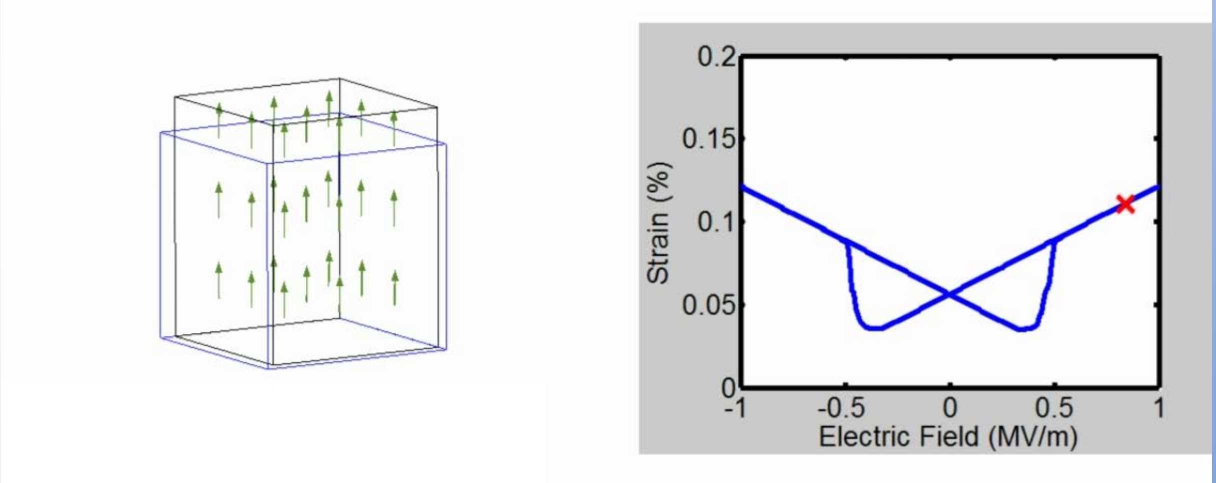


Linear Piezoelectric Example



Ferroelectric Example

Linear vs Ferroelectric

- Two videos illustrate key difference between ferroelectric and linear piezoelectric materials
- The first video is unable to switch polarization directions regardless of external fields, while the 2nd video exhibits a butterfly hysteresis loop behavior.

FEM Model

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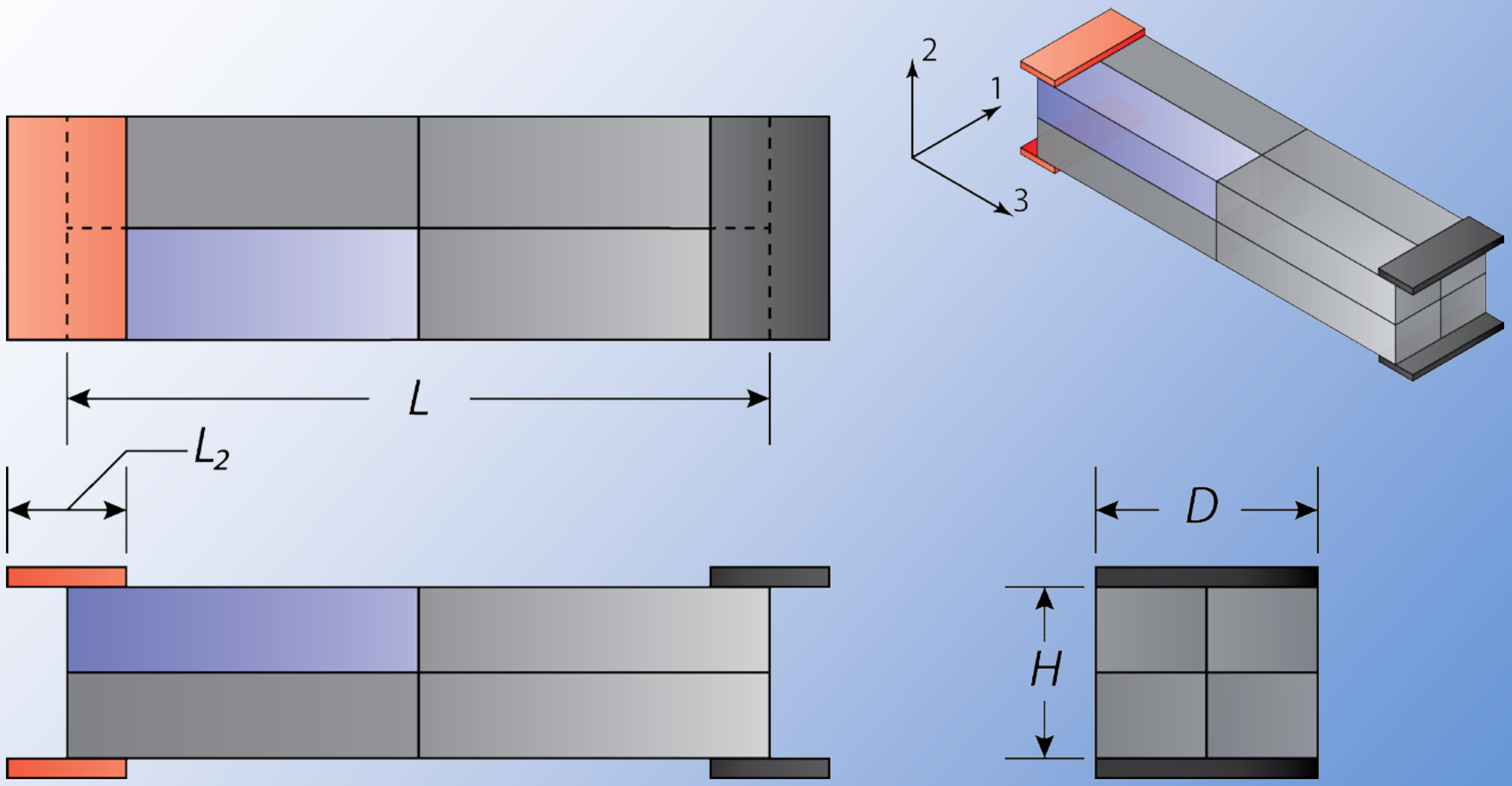

MFC Geometry Parameters to be Varied For FEM Simulations

FEM Model

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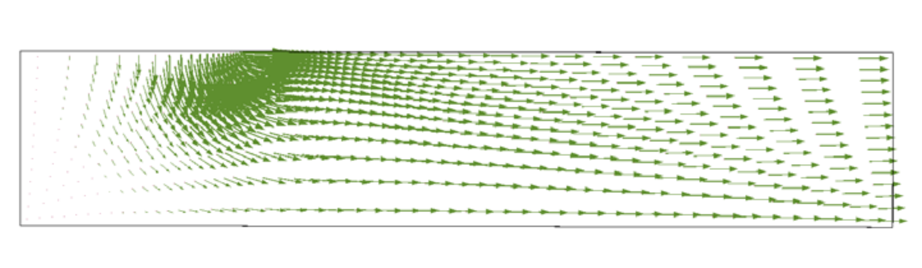
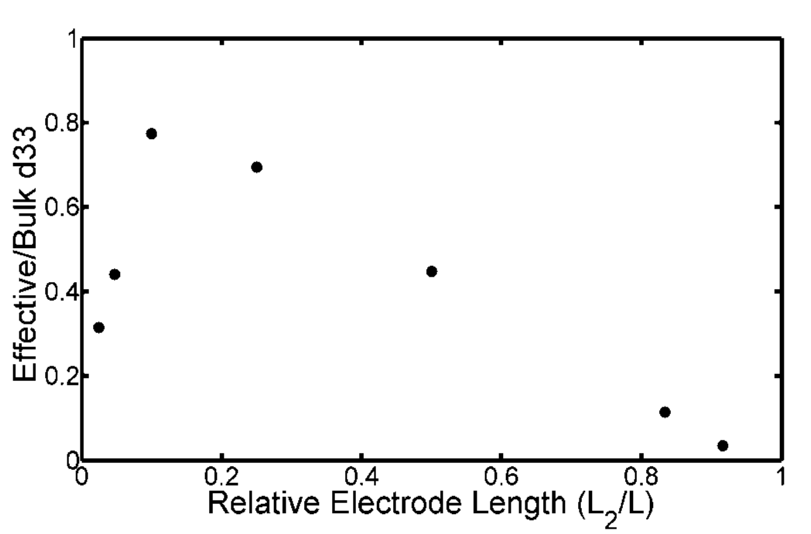
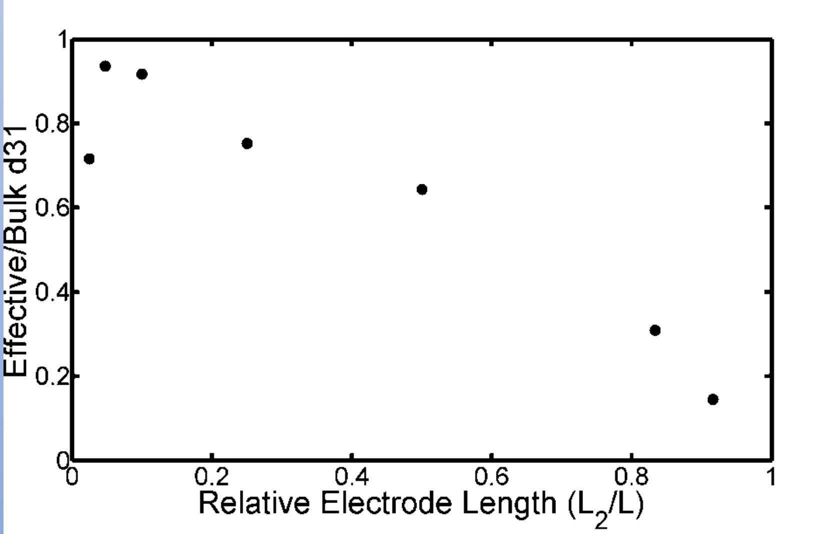
Varying L_2/L

- *From initial observation of dead region it makes sense that at L2/L increases that d33 would go down*
- *Why does it peak at a non zero maximum?*
- *L2/L was accomplished by holding L and other parameters constant and varying L2. Thus other ratios changed L2/D and L2/H*







Remnant Polarization Evolution

FEM Model

Explanation

- D2 is limited by the saturation polarization of the material
- This is only slightly larger than the remnant polarization value of 0.35 C/m^2.
- When the electrode contact area (A_2) is less than the fiber cross sectional area (A_1) , the fiber cannot be polarized
- Ideally $2L_2/H=1$ for smallest electrode

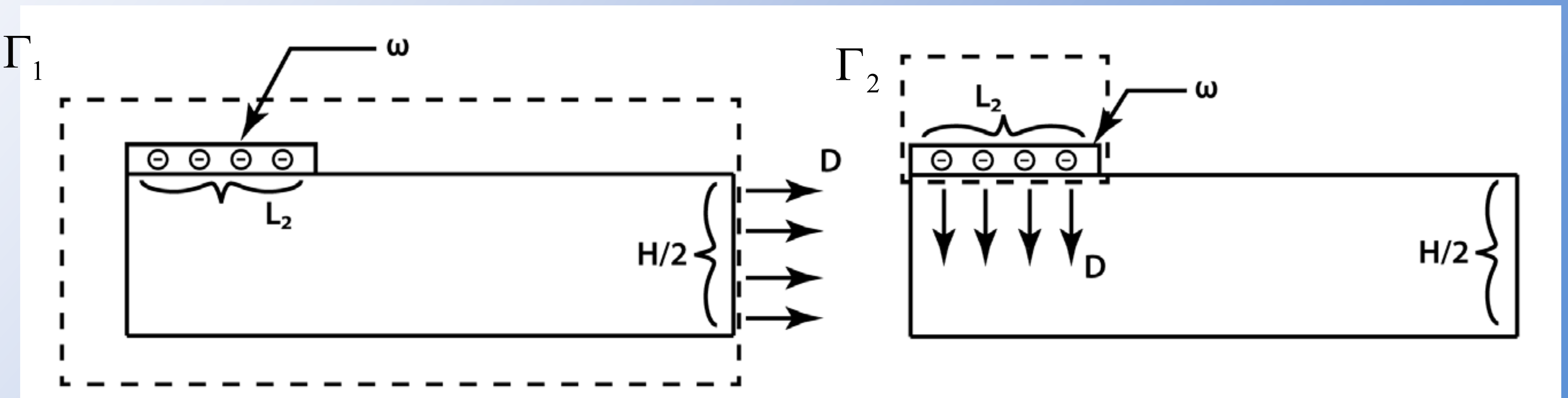
Gauss' Law

$$Q = \int_{\Gamma_1} D_1 \cdot dA = \int_{\Gamma_2} D_2 \cdot dA$$

$$Q \approx D_1 A_1$$

$$Q \approx D_2 A_2$$

$$D_2 \approx \frac{D_1 A_1}{A_2}$$



Gauss' law applied to the same material under the same boundary conditions.

FEM Model

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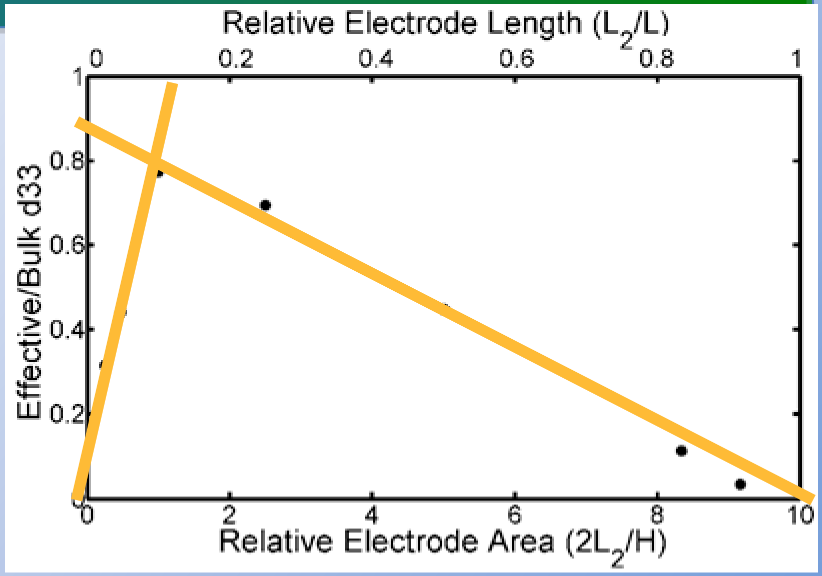
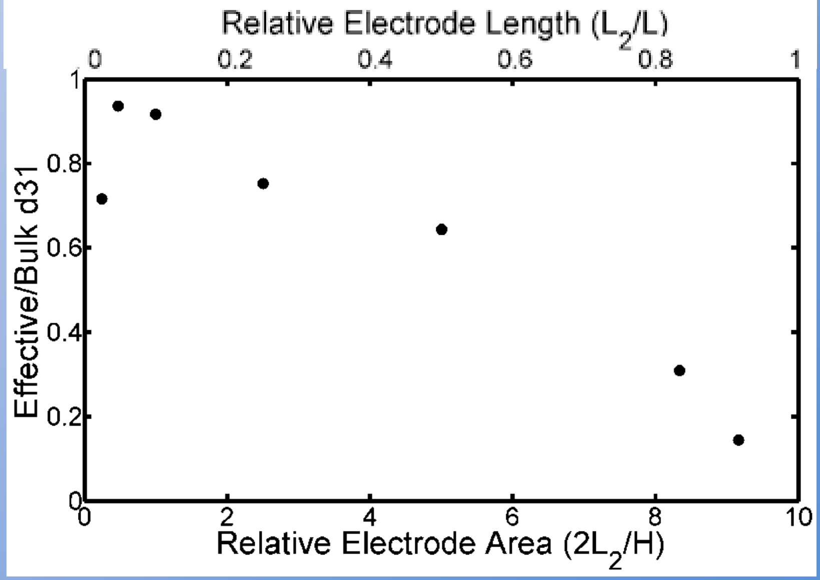
Varying $2L_2/H$

- Plotting a variation of the relative electrode area, $2L_2/H=1$ shows maximum
- For single sided electrode, $2L_2/H=1$ doesn't work. To equate electrode area to cross sectional area, $L_2/H=1$.
- D33 is highly dependent on two parameters. A fight between relative electrode area and relative electrode length.
- What about the fiber other parameters? Fiber length to depth?





Model validation studies

Example IDEs Ordered

Parametric Tests

- *To confirm FEM model predictions, 50 interdigitated PZT-5H plates ordered.*
- *The plates have various patterned electrodes as shown below.*
- *Tests currently underway*

Height 1

	L2/H	1.5	0.75	0.5	0.25	0.141667
(L-L2)/H						
1		Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
2		Specimen 6	Specimen 7	Specimen 8	Specimen 9	Specimen 10
2.5		Specimen 11	Specimen 12	Specimen 13	Specimen 14	Specimen 15
3		Specimen 16	Specimen 17	Specimen 18	Specimen 19	Specimen 20
3.5		Specimen 21	Specimen 22	Specimen 23	Specimen 24	Specimen 25

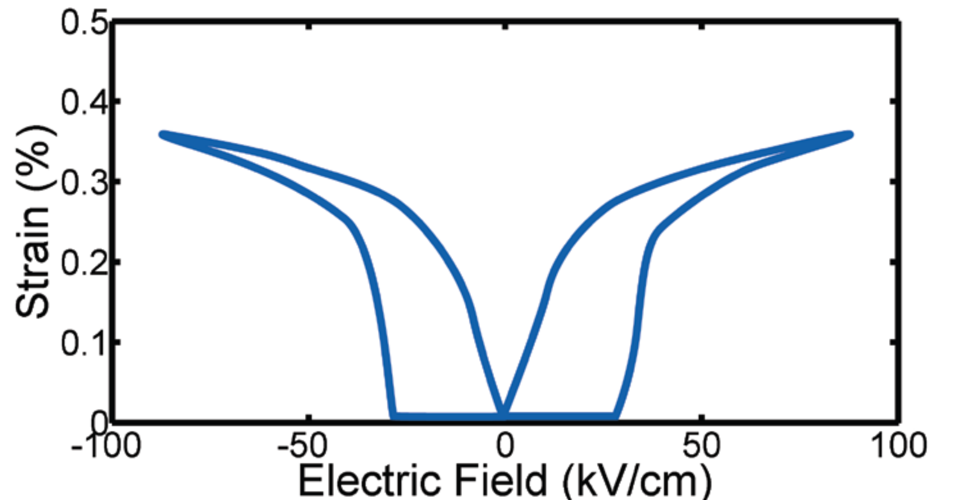
Height 2

	L2/H	1.5	0.75	0.5	0.25	0.141667
(L-L2)/H						
1		Specimen 26	Specimen 27	Specimen 28	Specimen 29	Specimen 30
2		Specimen 31	Specimen 32	Specimen 33	Specimen 34	Specimen 35
2.5		Specimen 36	Specimen 37	Specimen 38	Specimen 39	Specimen 40
3		Specimen 41	Specimen 42	Specimen 43	Specimen 44	Specimen 45
3.5		Specimen 46	Specimen 47	Specimen 48	Specimen 49	Specimen 50

New materials for optimizing desired self-latching behavior

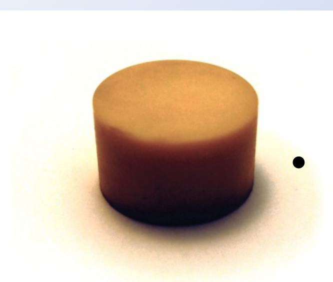
Die For PZT Manufacture

PLSnZT Strain Profile



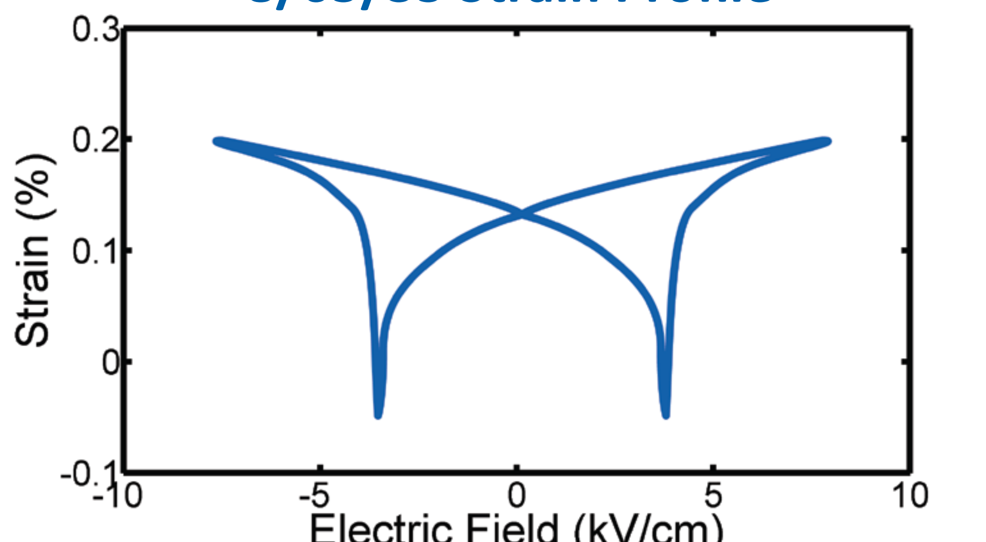
Exploration of Material

- New materials being explored for use in MFC. Two such are PLSnZT and 8/65/35 PLZT.
  - PLSnZT has large strain jumps due to phase transformations
  - 8/65/35 is a soft PLZT and would be useful for the latching effect.

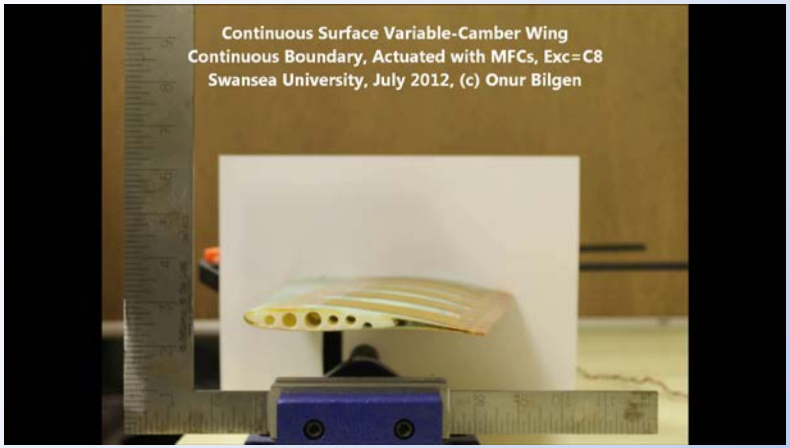


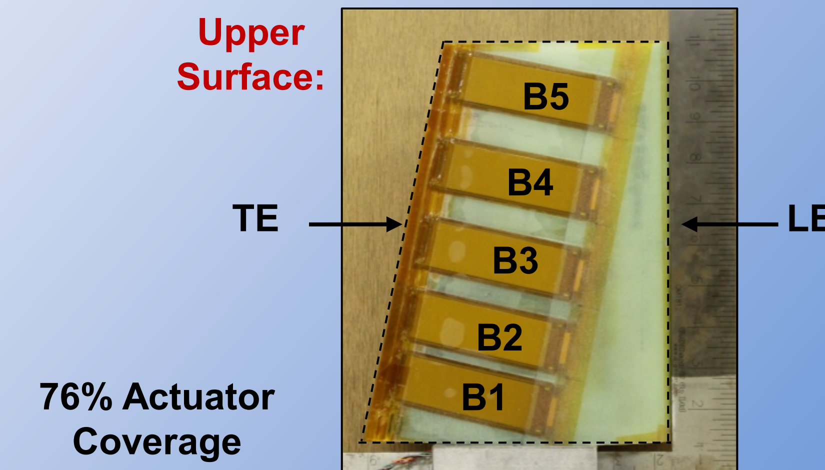
PLSnZT Material

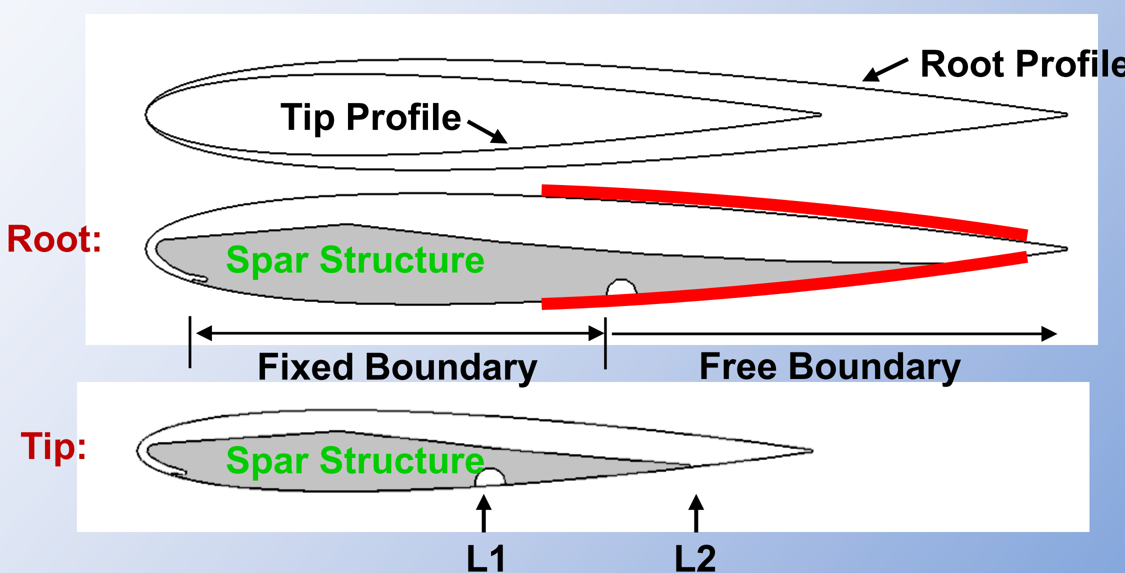
8/65/35 Strain Profile

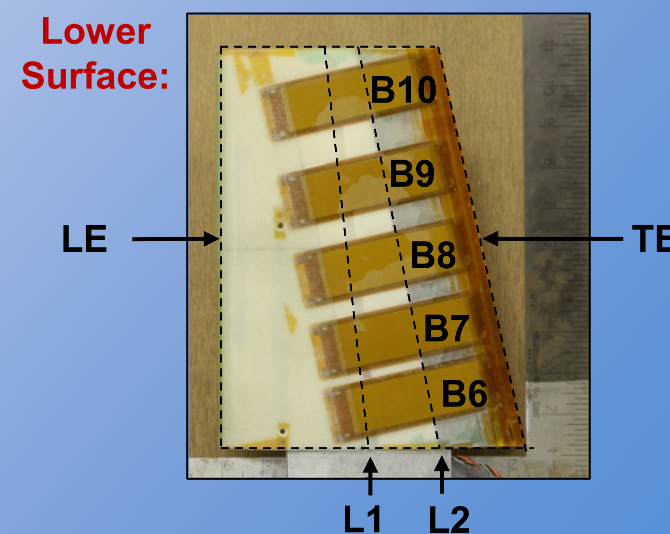


Solid-state variable camber piezocomposite airfoil









Ref: Bilgen, 2013

Phase I Summary and Status

- Phase I objectives:
  - Self latching piezocomposite proof-of-concept (non-optimized) demonstrated experimentally
  - Experimental validation of nonlinear FEM model underway:
    - Parametric actuator test coupon fabrication (100 test articles) complete, 6/2013.
    - Testing underway, 7/2013.
    - Validated model will be used to design electrodes for optimized self-latching actuator package (est. 8/2013)
  - “Exotic” piezoceramic material fabrication for improved self-latching actuator complete, 7/2013.
    - Materials to be incorporated into self-latching specimens in August.
  - Active airfoil preliminary concept defined
    - Self-latching piezocomposite can be a “drop-in” replacement for standard MFC in Bilgen deformable airfoils

Phase II future work

- Phase II objectives:
  - NASA/UCLA to optimize “exotic” self-latching piezocomposite actuator
  - Prof. Bilgen (ODU) brought on board to design active airfoils
  - Set-and-hold capability of self-latching airfoils to be validated in low-speed wind tunnel tests at ODU
    - Baseline and optimized self-latching piezocomposites to be tested
- Planned publications/invention disclosures:
  - NTR filed (NTR 1375456665, 2 August 2013)
  - NASA TM on Phase I work (October 2013)
  - Conference presentations TBD (NASA travel dependent)
- <u>Cross-cutting applications interest:</u>
  - *Self-latching piezocomposite technology is cross-cutting with space and adaptive optics applications*.
  - STMD funding sources to be sought to develop space applications.

Questions?